

History and new ideas for exotic particles

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Abstract

Basic 1966 physics of Sakharov, Zeldovich and Nambu updated by QCD with constituent-quark quasiparticles having effective masses fits all masses and magnetic moments of ground state meson and baryons having no more than one strange or heavy quark Flavor antisymmetry explains absence of low-lying exotics and suggests diquark-triquark model and two-state model for Θ^+ pentaquark. Variational approach gives mass bounds for other pentaquarks.

I. INTRODUCTION - WHAT CAN QED TEACH US ABOUT QCD?

QCD is a Great Theory, but how do we connect it with experiment or find approximations I recall Yoshio Yamaguchi's response in 1960 when asked whether there had been any thought

at CERN about a possible breakdown of QED at small distances: “No. . Many calculations. No thought.”

What can we learn from QED; a Great Theory that everyone knows how to connect with experiment? We know how isolated free electrons behave and carry currents. But nobody could explain the fractional Hall effect until Robert Laughlin told us the Hall Current is not carried by single electrons but by quasiparticles related to electrons by a complicated transformation.

Nobody has ever seen an isolated free quark. Experiments tell us that baryons are qqq and mesons are $q\bar{q}$ but these are not the current quarks whose fields appear in the QCD Lagrangian. Are these quarks complicated quasiparticles related to current quarks by a complicated transformation? Nobody knows. Is Hadron Spectroscopy Waiting for Laughlin? Does QCD need another Laughlin to tell us what constituent quarks are?

II. THE 1966 BASIC PHYSICS OF HADRON SPECTROSCOPY

A. The QCD-updated Sakharov-Zeldovich mass formula

A unified mass formula for both meson and baryon ground state masses [1] updated by DeRujula, Georgi and Glashow [2] (DGG) using QCD arguments relating hyperfine splittings to constituent quark effective masses [3] and baryon magnetic moments showed that all are made of the same quarks [1] and gave remarkable agreement with experiment including three magnetic moment predictions with no free parameters [4,5]

$$M = \sum_i m_i + \sum_{i>j} \frac{\vec{\sigma}_i \cdot \vec{\sigma}_j}{m_i \cdot m_j} \cdot v_{ij}^{hyp} \quad (1)$$

$$\begin{aligned} \langle m_s - m_u \rangle_{Bar} &= M_\Lambda - M_N = 177 \text{ MeV} \\ \langle m_s - m_u \rangle_{mes} &= \frac{3(M_{K^*} - M_\rho) + M_K - M_\pi}{4} = 180 \text{ MeV} \end{aligned} \quad (2)$$

$$\begin{aligned} \langle m_s - m_u \rangle_{Bar} &= \frac{M_N + M_\Delta}{6} \cdot \left(\frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} - 1 \right) = 190 \text{ MeV} \\ \langle m_s - m_u \rangle_{mes} &= \frac{3M_\rho + M_\pi}{8} \cdot \left(\frac{M_\rho - M_\pi}{M_{K^*} - M_K} - 1 \right) = 178 \text{ MeV}, \end{aligned} \quad (3)$$

$$\left(\frac{m_s}{m_u}\right)_{Bar} = \frac{M_\Delta - M_N}{M_{\Sigma^*} - M_\Sigma} = 1.53 = \left(\frac{m_s}{m_u}\right)_{mes} = \frac{M_\rho - M_\pi}{M_{K^*} - M_K} = 1.61 \quad (4)$$

$$\begin{aligned} \mu_\Lambda &= -0.61 \text{ n.m.} = -\frac{\mu_p}{3} \cdot \frac{m_u}{m_s} = -\frac{\mu_p}{3} \frac{M_{\Sigma^*} - M_\Sigma}{M_\Delta - M_N} = -0.61 \text{ n.m.} \\ \mu_p + \mu_n &= 0.88 \text{ n.m.} = \frac{M_p}{3m_u} = \frac{2M_p}{M_N + M_\Delta} = 0.865 \text{ n.m.} \\ -1.46 &= \frac{\mu_p}{\mu_n} = -\frac{3}{2}, \end{aligned} \quad (5)$$

The same value $\pm 3\%$ for $m_s - m_u$ is obtained from four independent calculations. The same value $\pm 2.5\%$ for $\frac{m_s}{m_u}$ is obtained from meson and baryon masses. The same approach for $m_b - m_c$ gives

$$\begin{aligned} \langle m_b - m_c \rangle_{Bar} &= M(\Lambda_b) - M(\Lambda_c) = 3341 \text{ MeV} \\ \langle m_b - m_c \rangle_{mes} &= \frac{3(M_{B^*} - M_{D^*}) + M_B - M_D}{4} = 3339 \text{ MeV} \end{aligned} \quad (6)$$

B. Two Hadron Spectrum puzzles -Why qqq and $q\bar{q}$?

1. The Meson-Baryon Puzzle - The qq and $\bar{q}q$ forces bind both mesons and baryons differently. A vector interaction gives equal and opposite forces; a scalar or tensor gives equal attractions for both.
2. Exotics Puzzle - No low-lying hadrons with exotic quantum numbers have been observed; e.g. no $\pi^+\pi^+$ or K^+N bound states.

Nambu solved both puzzles [6] in 1966, related mesons and baryons and eliminated exotics by introducing color and a two-body non-abelian-gauge interaction with the color-factor of one-gluon exchange.

A unified treatment of qq and $\bar{q}q$ interactions binds both mesons and baryons with the same forces. Only qqq and $q\bar{q}$ are stable in any single-cluster model with color space factorization. Any color singlet cluster that can break up into two color singlet clusters loses

no color electric energy and gains kinetic energy. The Nambu color factor does not imply dynamics of one-gluon exchange. Higher order diagrams can have same color factor

Looking beyond bag or single-cluster models for possible molecular bound states Lipkin(1972) lowered the color-electric potential energy in potential models by introducing color-space correlations; e.g, $q\bar{q}q\bar{q}$ at corners of a square, but not enough to compensate for the kinetic energy [7]

C. Important systematics in the experimental spectrum

A large spin-dependent interaction ≈ 300 MeV but a very weak interaction ≈ 2 MeV binding normal hadrons.

$$M(\Delta) - M(N) \approx 300 MeV \gg M(n) + M(p) - M(d) \approx 2 MeV \quad (7)$$

D. Conclusions from basics - What we do know and don't

We know the low-lying hadron spectrum is described by quasiparticles called quarks with a linear effective mass term and a hyperfine interaction with a one-gluon exchange color factor. Only color singlet and 3^* color factors arise in the $(\bar{q}q)$ and (qqq) states which behave like neutral atoms with a strong color electric field inside hadrons and none outside. No molecular bound states arise in the simplest cases. A strong spin-dependent interaction is crucial to understanding the spectrum

We don't know what these quarks are and the low-lying hadron spectrum provides no direct experimental information on $(\bar{q}q)_8$ and $(qq)_6$ interactions needed for multiquark exotic configurations.

III. QCD GUIDE TO THE SEARCH FOR EXOTICS

A. Words of Wisdom from Wigner and Bjorken

Wigner said: “With a few free parameters I can fit an elephant. With a few more I can make him wiggle his trunk”

His response to questions about a particular theory he did not like was:

“I think that this theory is wrong. But the old Bohr - Sommerfeld quantum theory also wrong. It is hard to see how we could have reached the right theory without going through that stage’.

In 1986 Bjorken noted how a $q\bar{q}$ created in e^+e^- annihilation fragments into hadrons. The quark can pick up an antiquark to make a meson. or a quark to make diquark. The diquark can pick up another quark to make a baryon but might pickup an antiquark to make a “triquark” bound in a color triplet state. Picking up two more quarks makes a pentaquark

BJ asked: “Should such states be bound or live long enough to be observable as hadron resonances? What does quark model say?”

B. What the quark model says about exotics

To consider the possible mass difference between the Θ^+ and a separated KN system, first put a K^+ and a neutron close together and keep the $u\bar{s}$ in the kaon and the udd in the neutron coupled to color singlets. Nothing happens because color singlet states behave like neutral atoms with negligible new interactions. Next change color-spin couplings while keeping an overall color singlet and search for the minimm energy. Use a variational approach with wave functions having the same spatial two-body density matrix elements as those in the observed mesons and baryons. Experimental hadron mass differences are then used to determine all parameters and look for possible bound states.

This approach finds no possibility for a K^+n bound state. But the same method shows that this trial wave function for the D_s^-p system gives a lower hyperfine potential energy

for the anticharmed strange pentaquark ($\bar{c}suud$) over the separated $D_s^- p$. Whether this is enough to compensate for the kinetic energy required to localize the state is unclear and highly model dependent with too many unknown parameters as soon as the requirements on the two-body density matrix are relaxed .

This anticharmed strange pentaquark [8] and Jaffe's H dibaryon [9] became the subjects of experimental searches. Although Fermilab E791 did not find convincing evidence [10] for the $\bar{c}suud$ pentaquark, the possibility is still open that this stable bound pentaquark exists and needs a better search.

The existence of the Θ^+ showed that wave functions with the same two-body density matrix for all pairs did not work and a two cluster model was needed to separate the uu and dd pairs that have a repulsive short-range hyperfine interaction. This led to the diquark-triquark model [4,5]..

C. Crucial role of color-magnetic interaction

1. QCD motivated models show same color-electric interaction for large multiquark states and separated hadrons and no binding. Only short-range color-magnetic interaction produces binding.
2. Jaffe [9] (1977) extended DGG with same color factor to multiquark sector in a single cluster or bag model, defined $(\bar{q}q)_8$ and $(qq)_6$ interactions, explained absence of lowlying exotics and suggested search for H dibaryon $uuddss$.
3. Jaffe's model extended to heavy quarks and flavor-antisymmetry principle [11] suggested exotic tetraquarks and anticharmed strange pentaquark [8] ($\bar{c}uuds$) (1987)

D. Flavor antisymmetry principle - No leading exotics

The Pauli principle requires flavor-symmetric quark pairs to be antisymmetric in color and spin at short distances. Thus the short-range color-magnetic interaction is always

repulsive between flavor-symmetric pairs.

1. Best candidates for multiquark binding have minimum number of same-flavor pairs

(a) Nucleon has only one same-flavor pair

(b) $\Delta^{++}(uuu)$ has three same-flavor pairs

Costs 300 MeV relative to nucleon with only one.

(c) Deuteron separates six same-flavor pairs into two nucleons

Only two same-flavor pairs feel short range repulsion.

(d) $H(uud\bar{d}s)$ has three same-flavor pairs. Optimum for light quark dibaryon

(e) The $(uuds\bar{c})$ pentaquark has only one same-flavor pair

2. Pentaquark search. $(uuds\bar{c})$ pentaquark has same binding as H.

(a) Quark model calculations told experimenters to look for $(uuds\bar{c})$ pentaquark; not the Θ^+ .

(b) $\Theta^+ (uudd\bar{s})$ has two same-flavor pairs. Too many for a single baryon.

(c) Calculations motivating the $(uuds\bar{c})$ pentaquark search found no reason to look for $(uudd\bar{s})$

Ashery's E791 search for $\bar{c}uuds$ found events [10]; not convincing enough.

Better searches for this pentaquark are needed; e.g. searches with good vertex detectors and particle ID [8].

Any proton emitted from secondary vertex is interesting. One gold-plated event not a known baryon is enough; No statistical analysis needed.

IV. THE Θ^+ WAS FOUND! WHAT CAN IT BE?

Following Wigner's guidance to understand QCD and the pentaquark, find a good wrong model that can teach us; stay away from free parameters

A. The skyrmion model

Experimental search motivated by another “wrong model”. Skyrmion [12] has no simple connection with quarks except by another “wrong model”. The $1/N_c$ expansion invented [13] pre-QCD to explain absence of free quarks.

-The binding Energy of $q\bar{q}$ pairs into mesons $E_M \approx g^2 N_c$.

At large N_c the cross section for meson-meson scattering breaking up a meson into its constituent quarks is

$$\sigma[MM \rightarrow M + q + \bar{q}] \approx g^2 \frac{E_M}{N_c} \approx 0 \quad (8)$$

But $\frac{1}{N_c} = \frac{1}{3}$; $\frac{\pi}{N_c} \approx 1$ This is NOT A SMALL PARAMETER!

B. How to explain Θ^+ with quarks - The two-state model

No bag or single cluster model with the same flavor-space correlation for all quarks can work. Keeping same-flavor pairs apart led to diquark-triquark model with (ud) diquark separated from remaining $(ud\bar{s})$ triquark with triquark color-spin coupling minimizing color-magnetic energy [4,5].

Noting two different color-spin couplings for triquark with roughly equal color-magnetic energy leads naturally to a two-state model [14].

Let $|\Theta_1\rangle$ and $|\Theta_2\rangle$ denote an orthonormal basis for the two diquark-triquark states with different triquark color-spin couplings.

The mass matrix eigenstates can be defined with a mixing angle ϕ

$$\begin{aligned} |\Theta\rangle_S &\equiv \cos \phi \cdot |\Theta_1\rangle + \sin \phi \cdot |\Theta_2\rangle \\ |\Theta\rangle_L &\equiv \sin \phi \cdot |\Theta_1\rangle - \cos \phi \cdot |\Theta_2\rangle \end{aligned} \quad (9)$$

Loop diagram via the KN intermediate state $\Theta_i \rightarrow KN \rightarrow \Theta_j$ gives the mass matrix and mass eigenstates

$$M_{ij} = M_o \cdot \langle \Theta_i | T | KN \rangle \langle KN | T | \Theta_j \rangle \quad (10)$$

$$\begin{aligned} |\Theta\rangle_S &= C[\langle KN | T | \Theta_1 \rangle \cdot |\Theta_1\rangle + \langle KN | T | \Theta_2 \rangle \cdot |\Theta_2\rangle] \\ |\Theta\rangle_L &= C[\langle KN | T | \Theta_2 \rangle \cdot |\Theta_1\rangle - \langle KN | T | \Theta_1 \rangle \cdot |\Theta_2\rangle] \end{aligned} \quad (11)$$

where C is a normalization factor

Then $\langle KN | T | \Theta_1 \rangle \cdot \langle KN | T | \Theta_2 \rangle - \langle KN | T | \Theta_2 \rangle \cdot \langle KN | T | \Theta_1 \rangle = 0$

Thus $\langle KN | T | \Theta \rangle_L = 0$; the state Θ_L is decoupled from KN and its decay into KN is forbidden.

The state Θ_S with normal hadronic width can escape observation against continuum background.

But there are no restrictions on couplings to K^*N . Both $|\Theta_L\rangle$ and $|\Theta_S\rangle$ are produced without suppression by K^* exchange.

Advantages of the two-state model

1. Explains narrow width and strong production
2. Arises naturally in a diquark-triquark model

where two states have different color-spin couplings

3. Loop diagram mixing via KN decouples one state from KN
4. Broad state decaying to KN not seen
5. Narrow state coupled weakly to KN produced via K^* exchange

C. A variational approach for the Pentaquark Multiplet

Apply the QM Variational Principle to the exact (unknown) hamiltonian H and unknown exact wave function $|\Theta^+\rangle$ with three simple assumptions [15]:

1. Assume Θ^+ and Ξ^{--} are pentaquarks $uudd\bar{s}$ and $ssdd\bar{u}$

2. Assume Θ^+ and Ξ^{--} are degenerate in $SU(3)_f$ limit.
3. Assume $SU(3)$ breaking changes only quark masses and leaves QCD color couplings unchanged in H .

$$\langle \Theta^+ | T_{u \leftrightarrow s}^\dagger H T_{u \leftrightarrow s} - H | \Theta^+ \rangle \approx m_s - m_u + \langle \Theta^+ | \delta V_{\bar{s} \rightarrow \bar{u}}^{hyp} + \delta V_{u \rightarrow s}^{hyp} | \Theta^+ \rangle \quad (12)$$

where the $SU(3)_f$ transformation $T_{u \leftrightarrow s}$ interchanges u and s flavors and $\delta V_{\bar{s} \rightarrow \bar{u}}^{hyp}$ and $\delta V_{u \rightarrow s}^{hyp}$ denote the change in the hyperfine interaction under the transformations $\bar{s} \rightarrow \bar{u}$ and $u \rightarrow s$ respectively. Define a trial wave function

$$|\Xi_{var}^{--}\rangle \equiv T_{u \leftrightarrow s} \cdot |\Theta^+\rangle \quad (13)$$

The variational Principle gives an upper bound for $M(\Xi^{--})$

$$\begin{aligned} M(\Xi^{--}) &\leq \langle \Xi_{var}^{--} | H | \Xi_{var}^{--} \rangle = \langle \Xi_{var}^{--} | H | \Xi_{var}^{--} \rangle + M(\Theta^+) - \langle \Theta^+ | H | \Theta^+ \rangle \\ M(\Xi^{--}) - M(\Theta^+) &\leq \langle \Theta^+ | T_{u \leftrightarrow s}^\dagger H T_{u \leftrightarrow s} - H | \Theta^+ \rangle \\ M(\Xi^{--}) - M(\Theta^+) &\leq m_s - m_u + \langle \Theta^+ | \delta V_{\bar{s} \rightarrow \bar{u}}^{hyp} + \delta V_{u \rightarrow s}^{hyp} | \Theta^+ \rangle, \end{aligned} \quad (14)$$

where we have substituted eq. (12) for the $SU(3)_f$ breaking piece of H . From quark model hadron spectroscopy and simple assumptions about $SU(3)$ breaking

$$\begin{aligned} m_s - m_u &\leq M(\Lambda) - M(N) \\ \langle \Theta^+ | \delta V_{\bar{s} \rightarrow \bar{u}}^{hyp} | \Theta^+ \rangle &\leq 0 \\ \langle \Theta^+ | \delta V_{u \rightarrow s}^{hyp} | \Theta^+ \rangle &\leq 2 \cdot \langle ud_{S=0} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=0} \rangle, \end{aligned} \quad (15)$$

$$\begin{aligned} M(\Sigma^-) - M(\Lambda) &= \langle ud_{S=0} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=0} \rangle - \langle ud_{S=1} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=1} \rangle \\ &= \langle ud_{S=0} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=0} \rangle \cdot \left(1 - \frac{\langle ud_{S=1} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=1} \rangle}{\langle ud_{S=0} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=0} \rangle} \right) \\ M(\Sigma^{*-}) - M(\Delta^o) &= m_s - m_u + 2 \langle ud_{S=1} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=1} \rangle \end{aligned} \quad (16)$$

$$\begin{aligned}
M(\Xi^{--}) - M(\Theta^+) &\leq m_s - m_u + 2 \cdot \langle ud_{S=0} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=0} \rangle \\
M(\Xi^{--}) - M(\Theta^+) &\leq M(\Sigma^{*-}) - M(\Delta^o) + 2[M(\Sigma^-) - M(\Lambda)] \\
M(\Xi^{--}) - M(\Theta^+) &\leq 316 \text{MeV} \\
[M(\Xi^{--}) - M(\Theta^+)]_{(experiment)} &= 330 \text{MeV}
\end{aligned} \tag{17}$$

With $\sigma_i \cdot \sigma_j$ interaction, $\frac{\langle ud_{S=1} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=1} \rangle}{\langle ud_{S=0} | \delta V_{u \rightarrow s}^{hyp} | ud_{S=0} \rangle} = -\frac{1}{3}$

$$\begin{aligned}
M(\Xi^{--}) - M(\Theta^+) &\leq M(\Lambda) - M(N) + \frac{3}{2} \cdot [M(\Sigma^-) - M(\Lambda)] \\
M(\Xi^{--}) - M(\Theta^+) &\leq 299 \text{MeV} \\
[M(\Xi^{--}) - M(\Theta^+)]_{(experiment)} &= 330 \text{MeV}
\end{aligned} \tag{18}$$

Experiment violates both bounds!

Is an experiment or one of our assumptions wrong?

1. Θ^+ and Ξ^{--} not pentaquarks $uudd\bar{s}$ and $ssdd\bar{u}$?
2. Θ^+ and Ξ^{--} not degenerate in the $SU(3)_f$ limit?
3. Is our $SU(3)$ -breaking model wrong?

One possibility is the two-state model. The Θ^+ and Ξ^{--} are not in the same $SU(3)_f$ multiplet if the two nearly degenerate diquark-triquark multiplets mix differently

V. HEAVY FLAVOR PENTAQUARAKS - THE Θ_C CHARMED PENTAQUARK

We now use the variational approach to examine pentaquark states obtained by replacing the \bar{s} by \bar{c} or other heavy antiquarks in the exact Θ^+ wave function [16] and define a trial wave function

$$|\Theta_c^{var}\rangle \equiv T_{s \leftrightarrow c} \cdot |\Theta^+\rangle \tag{19}$$

We have the same light quark system and a different flavored antiquark. There is the same color electric field and a mass change.

The variational principle gives an upper bound for $M(\Theta_c)$

$$M(\Theta_c) \leq M(\Theta^+) + m_c - m_s + \langle V_{hyp}(\bar{c}) \rangle_{\Theta^+} - \langle V_{hyp}(\bar{s}) \rangle_{\Theta^+} \quad (20)$$

Hyperfine interaction inversely proportional to quark mass product,

$$\langle V_{hyp}(\bar{c}) \rangle = \frac{m_s}{m_c} \cdot \langle V_{hyp}(\bar{s}) \rangle \quad (21)$$

$$M(\Theta_c) - M(\Theta^+) \leq (m_c - m_s) \cdot \left(1 + \frac{|\langle V_{hyp}(\bar{s}) \rangle_{\Theta^+}|}{m_c} \right) \quad (22)$$

Now examine the difference between the mass and the decay threshold

$$\Delta E_{DN}(\Theta_c) = M(\Theta_c) - M_N - M_D$$

$$\Delta E_{KN}(\Theta^+) = M(\Theta^+) - M_N - M_K \approx 100 \text{ MeV}$$

$$\Delta E_{DN}(\Theta_c) - \Delta E_{KN}(\Theta^+) = M(\Theta_c) - M(\Theta^+) - M_D + M_K \quad (23)$$

$$\Delta E_{DN}(\Theta_c) \leq 0.7 \cdot |\langle V_{hyp}(\bar{s}) \rangle_{\Theta^+}| - 100 \text{ MeV} \quad (24)$$

Thus if $|\langle V_{hyp}(\bar{s}) \rangle_{\Theta^+}| \leq 140 \text{ MeV}$ the Θ_c is stable against strong decays.

But the $K^* - K$ mass difference tells us that in the kaon

$$|\langle V_{hyp}(\bar{s}) \rangle_{K(u\bar{s})}| \approx 300 \text{ MeV} \quad (25)$$

Is the hyperfine interaction of \bar{s} with four quarks in a Θ^+ comparable to $V_{hyp}(\bar{s})$ with one quark in a kaon?

This determines the stability of the Θ_c . Experiment will tell us about how QCD makes hadrons from quarks and gluons

VI. EXPERIMENTAL CONTRADICTIONS ABOUT THE Θ^+

Some experiments see the pentaquark [17] others definitely do not [18]. No theoretical model addresses why certain experiments see it and others do not. Comprehensive review [19] analyzes different models.

Further analysis is needed to check presence of specific production mechanisms in experiments that see the Θ^+ and their absence in those that do not [18]. One possibility is production and decay of a cryptoexotic $N^*(2400)$ with hidden strangeness [20] fitting naturally into P -wave (ud) diquark- $ud\bar{s}$ triquark model for the Θ^+ . The N^* is a (ds) diquark in the same flavor $SU(3)$ multiplet as the (ud) diquark in the Θ^+ in a D -wave with the $ud\bar{s}$ triquark. Its dominant decay would produce the Θ^+ in $K^-\Theta^+$ via the diquark transition $ds \rightarrow ud + K^-$. Decays like ΛK and ΣK would be suppressed by the centrifugal barrier forbidding a quark in the triquark from joining the diquark.

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